MID-HOLOCENE CLIMATE SIMULATIONS OVER BRAZIL USING THE ETA REGIONAL PALEOCLIMATE MODEL

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ABSTRACT

Paleoclimate simulations are generally performed using coarse global climate models. However, validation of these simulations using a local dataset may be penalized by the coarse grid of the global models. Using a regional climate model, which benefits from the use of higher resolution in a limited area and specific period of time, may help improve the validation of the simulations and help to understand the climate of the past. The objective of this study is to evaluate the Mid-Holocene (MH) simulations for Brazil at 20 km spatial resolution using the regional Eta Model. The simulations are produced by nesting the Eta Model to the National Institute for Space Research (INPE) Global Spectral Atmospheric Model at T062 resolution and 28 vertical levels. Both global and regional models used the same orbital parameters to produce the Milankovic Cycles based on the Berger parameterization. The models adopted the typical carbon dioxide values for the present time and the MH. Downscaling simulations were performed with the Eta Model, resulting in simulations of 2 periods of time, the Eta 0k (present) and the Eta 6k (MH), each 10 years long. The evaluation compares these simulations against proxy data and other paleoclimate model simulations for the region. The difference between the two simulations, 6k and 0k, provides the changes between the two climatic periods. The Eta simulations indicate that the climate during MH was more humid over Northeast Brazil; this agrees partially with paleoclimate data in eastern Northeast Brazil. The Amazon region simulations were mostly drier during MH, in agreement with the paleoclimate data. A weaker convergence of winds in the MH, with winds blowing from the Amazon toward Southeast Brazil, affected the formation and the positioning of the South Atlantic Convergence Zone. Consequently, the associated moisture transport toward the Southeast was smaller; this reduced precipitation in the Brazilian southeastern, central-west, and southern regions, which agrees with the proxy data. The Eta Model simulated a cooler climate for the MH over the Northeast, Central, Southeast, and South Brazil. However, this simulated temperature showed less agreement against proxy data. The Amazon region was slightly warmer, and other transition regions showed no climate change. Overall, the results show that this modified version of the Eta Model is suitable for paleoclimate studies and provides added value over the driver model.

Keywords: Regional paleoclimate; Eta Model simulations; Milankovic cycles; Berger parameterization.

RESUMO

SIMULAÇÕES CLIMÁTICAS DO HOLOCENO MÉDIO PARA O BRASIL UTILIZANDO O MODELO REGIONAL PALEOCLIMÁTICO ETA. Simulações paleoclimáticas geralmente são realizadas utilizando modelos climáticos globais de baixa resolução. No entanto, a validação dessas simulações usando um conjunto de dados local pode ser penalizada pela grade grosseira dos modelos globais. O uso de modelos climáticos regionais, que se beneficiam do uso de maior resolução em uma área limitada e período de tempo específico, pode ajudar a melhorar a validação das simulações e auxiliar no entendimento do clima passado. O objetivo deste trabalho é avaliar as simulações do Holoceno Médio (HM) para o Brasil em resolução espacial de 20 km usando o Modelo Regional Climático Eta . As simulações são produzidas aninhando o Modelo Eta ao Modelo Atmosférico Espectral Global do Instituto Nacional de Pesquisas Espaciais na resolução T062 e 28 níveis verticais. Ambos os modelos global e regional usaram os mesmos parâmetros orbitais para produzir os Ciclos de Milankovic com base na parametrização de Berger. Os modelos adotaram os valores típicos de dióxido de carbono para o tempo presente e o HM. Simulações de regionalização foram realizadas com o modelo Eta para dois períodos climáticos do tempo, o Eta 0k (presente) e o Eta 6k (HM), cada simulação com 10 anos de duração. A avaliação compara essas simulações com dados proxies e simulações de outros modelos paleoclimáticos para a região. A diferença entre as duas simulações, 6k – 0k, fornece as mudanças entre os dois períodos climáticos. As simulações do Eta indicam que o clima durante HM foi mais úmido no Nordeste do Brasil; isso concorda parcialmente com os dados paleoclimáticos no leste do Nordeste brasileiro. As simulações da região Amazônica sugerem condições mais secas durante HM, e também estão de acordo com os dados paleoclimáticos. O enfraquecimento da convergência de ventos, no HM, com ventos soprando da Amazônia em direção ao Sudeste do Brasil, afetou a formação e o posicionamento da Zona de Convergência do Atlântico Sul. O transporte de umidade associado, em direção ao Sudeste foi menor, o que reduziu a precipitação nas regiões Sudeste, Centro-Oeste e Sul do Brasil, o que concorda com os dados proxy. O modelo Eta simulou um clima mais frio para o HM nas regiões Nordeste, Centro, Sudeste e Sul do Brasil. No entanto, esta temperatura simulada mostrou menos concordância com os dados *proxy*. A região amazônica foi um pouco mais quente e outras regiões de transição não apresentaram mudanças climáticas significativas. No geral, os resultados mostraram que esta versão modificada do modelo Eta é adequada para estudos paleoclimáticos e fornece valor agregado em relação ao modelo global.

Palavras-chave: Paleoclima regional; Modelo Eta; Ciclos de Milankovic; Parametrização de Berger.

1 INTRODUCTION

Climate change is a significant and long-lasting change in the statistical distribution of a given climate variable, and changes may range from decades to millions of years. Understanding and assessing climate change are relevant as human activities have altered and impacted the world's environment.

Several factors control climate variability and change. These so-called climatic agents can be natural or anthropogenic. Natural climatic agents are induced by internal forcings, such as atmospheric or ocean circulations, volcano activities, or changes in surface albedo, or by external forcings, such as the orbital variation, solar cycle, or gravitational forces. Anthropogenic climate agents, which are directly linked to the increase in industrial activity and, consequently, to the pollutants released into the atmosphere (carbon dioxide - CO_2, nitrous oxide - N_2O, and methane

CH4), have been causing an increase in the global average temperature. There is no doubt that human activities have caused a substantial increase in greenhouse gas in recent decades (IPCC 2021). A specific climatic agent can contribute to heating the Planet, while another can contribute to cooling it, and their net effects on the global climatic system are still uncertain.

To better identify future climate variability, it is necessary to understand past climate variability. There are two main approaches to verifying long-term climate variation: the first is by examining paleoclimate records, also called paleoclimate indicators or proxies, which allow one to examine climate response to past forcings. The second approach is by using numerical climate models. These models help to examine the relationships between the various types of forcings and the responses of the climate system to the forcings. Thus, sensitivity tests can be carried out in which model orbital parameters and concentration of greenhouse gases (JOUSSAUME & TAYLOR 1995) are modified. The resulting climate change is due to changes in parameters or processes. These models are validated using those proxies, considering the uncertainties in these climate reconstructions. A coordinated effort toward paleoclimate modeling experiments (PMIP 2000) has been organized, and in their first phases, the Mid-Holocene was one of the periods of study (MASSON & JOUSSAUME 1997, VETTORETTI et al. 1998).

The Mid-Holocene (MH), a period of 6,000 years ago, is characterized by changes in the orbital parameters that led to natural climate change; it is the most studied period of the Quaternary. The MH was also considered a climatically stable period (SEPPÄ et al. 2005), as no glaciation or overheating occurred, but a period marked by average climatic characteristics similar to the current climate. Therefore, this is the period recommended for the initial tests to evaluate the model's skill in reproducing past climates.

The MH period differs from the present in the seasonal contrast modified by the incident solar radiation at the top of the atmosphere. It is a period marked by natural climate change through external forcing due to the change in the orbital parameters. The availability of paleoclimate data as proxies for this period makes it a suitable candidate to validate global climate models. A new set of proxy data, fully calibrated and updated for eastern South America, has been recently produced by GORENSTEIN et al. (2022). The data comprised of various measurements (speleothems, sediment cores marine, lacustrine, terrestrial, and soil samples from South America) resulted in more than one hundred proxies.

These climate models may help to provide an understanding of mechanisms of changes in climate in the past and, consequently, to understand the projections of future climate change.

MELO & MARENGO (2007) analyzed climate variations and change during the Mid-Holocene (MH) for South America (SA) using the atmospheric general circulation model (AGCM) from the Instituto Nacional de Pesquisas Espaciais (INPE) at a T062L28 resolution. The INPE simulations were done by modifying the orbital parameters and CO_2 concentration, using typical MH values used by other MH simulations studies, and using the sea surface temperature (SST) data from two different groups: one from the Atmospheric Model Intercomparison Project (AMIP, GATES et al. 1998), AMIP SST, and the other generated by the ocean component of the Institute Pierre Simon Laplace coupled ocean-atmosphere model, IPSL SST. The simulations were compared against the MH climate simulations from the Paleoclimate Modeling Intercomparison Project (PMIP) Phases I and II and paleoclimate indicators. The INPE AGCM simulated a wetter climate over Northeast Brazil almost all year, except in autumn when simulations showed a more northward displacement of the Intertropical Convergence Zone (ITCZ). This northward displacement was associated with weakening of the northeasterly trade winds and the moisture transport from the Tropical Atlantic into the Amazon region. The simulations produced a drier climate in the Amazon region except in autumn and spring in the MH. The reduction of the precipitation significantly impacts the moisture transport from the Amazon basin toward the Parana-Plata basin and, consequently, on the alignment of the South Atlantic Convergence Zone (SACZ). Therefore, the simulated precipitation reduction in the Amazon caused a reduction of the SACZ precipitation. This result was obtained using the AMIP's SST, whereas the SACZ presence was not detected in the experiment using IPSL's SST. As for the air temperature, a signal of cooling all along the year in the MH was simulated over Brazil, except in the western Amazon region, which suggests weak warming (MELO & MARENGO 2007).

The interglacial experiments for CMIP6 consisted of timeslice experiments in the years 6,000 and 127,000 before the present. The present period is defined as around 1950. These periods are referred to as 6 ka (Mid-Holocene) and 127 ka (Last Interglacial 127k). The Mid-Holocene period has been the focus of model simulations, model–model comparisons, paleo-data synthesis, and model–data comparisons since the beginning of PMIP. Works such as those done by FOLLAND et al. (2001), HEGERL et al. (2007), JANSEN & WEAVER (2005), FLATO et al. (2013), and MASSON-DELMOTTE et al. (2013) have contributed to model evaluation and understanding of climate change in the last three significant assessments of the Intergovernmental Panel on Climate Change. Still, there are knowledge gaps in coverage from continental regions, particularly in the Southern Hemisphere (SH), but this situation is likely to improve soon (FLANTUA et al. 2015, HERBERT & HARRISON 2016). Knowledge of ocean conditions during the Mid-Holocene is poor due to uncertainties in observations and methodologies (HESSLER et al. 2014, JONKERS & KUCERA 2015, ROSELL-MELE & PRAHL 2013). OTTO-BLIESNER et al. (2017) mentioned that insolation during the Mid-Holocene enhanced seasonal contrast in the Northern Hemisphere and reduced seasonal contrast in the Southern Hemisphere, which resulted in warmer NH summers.

The validation of the coarse global paleoclimate model simulations against proxy data has been limited due to the local character of the proxies, as the topography or vegetation land cover can affect these. Regional Paleoclimate Modeling has been applied to improve this validation and the understanding of the physical processes that produced those proxy data (LUDWIG et al. 2019). Simulations of the Mid-Holocene climate have been simulated by regional climate models (RCM) over North America (DIFFENBAUGH et al. 2006), Africa (PATRICOLA & COOK 2007), Iran (FALLAH et al. 2017), and China (YU et al. 2014). They have produced added value, particularly in hydrological aspects of the past climate. However, no RCM has yet been simulated this past period over Brazil. The Eta RCM has been applied to seasonal forecasts (CHOU et al. 2005) and climate change simulations (PESQUERO et al. 2010, CHOU et al. 2012, MARENGO et al. 2012, CHOU et al. 2014a, b) but has not been tested for past climate.

This work aims to assess the MH climate variability over Brazil simulated by the Eta Regional Climate Model. The evaluation compares the paleoclimate indicators and the simulated climate characteristics in the MH period.

2 METHODOLOGY

Regional Climate Models require lateral boundary conditions to drive the limited area higher resolution simulations. Below are the descriptions of the Global Climate Model used as the driver of the Eta Regional Climate Model and the astronomical model parameters.

2.1 Global Climate Model

The global model used for the climate simulations is INPE's Global Climate Model (CAVALCANTI et al. 2002, MARENGO et al. 2003, MARENGO 2005). That is a spectral model, and the chosen resolution is the triangular truncation of 62 waves in the horizontal, which is approximately 200 km resolution near the equator, and 28 sigma levels in the vertical. The AGCM uses the surface scheme the Simple Simplified Biosphere Model (SSiB) that considers the influence of the vegetation from a more sophisticated viewpoint (XUE et al. 1991). The parameterizations used in the model are shortwave radiation, according to LACIS & HANSEN (1974), and modified by RAMASWAMY & FREIDENREICH (1992); longwave radiation by HARSHVARDHAN et al. (1987); the Kuo scheme for deep convection (KUO 1974); shallow convection, according to TIEDTKE (1983). More information on this model and its ability to simulate South American climate can be found in CAVALCANTI et al. (2002) and MARENGO et al. (2003). The boundary conditions, sea surface temperature (SST), and the initial conditions were taken from the National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis (KALNAY et al. 1996). The current value of the CO_2 concentration used in the model is 360 ppm for comparison with existing simulations.

Two 40-year simulations were carried out using the INPE's Global Model to reproduce the global climate and produce boundary conditions for the regional Eta Model. The first simulation, Model 0k, the present climate, was set up as the control run. The second simulation, Berger 0k, also the present climate, contains the Berger scheme (BERGER 1978). The Berger scheme calculates the values of the orbital parameters: obliquity, eccentricity, and precession by taking into account the year of the simulation; in this case, 1950.

MELO & MARENGO (2008) evaluated these global climate simulations and analyzed the climate changes due to changes in the orbital parameters of the Earth during the MH period. They noticed changes in the seasonal cycle of insolation in both hemispheres in comparison to 0k. During the MH, the Southern Hemisphere experienced an attenuation of the seasonal cycle, whereas the Northern Hemisphere experienced an intensification. The comparison between the INPE AGCM simulations against palaeoclimate indicators and the PMIP palaeoclimate simulations showed that INPE AGCM could simulate the main large-scale climate patterns of the MH period (MELO & MARENGO 2008) .

2.2 Regional Climate Model

The climate over most of South America (between 12ºN and 50ºS, and 85ºW and 28ºW) was simulated using the Eta Regional Climate Model (CHOU et al. 2005, MESINGER et al. 2012). The vertical Eta coordinate (MESINGER 1984) adopted by the Eta RCM is suitable for South America, where the Andes Cordillera exhibits complex and steep slopes. No paleoclimate simulations have been investigated previously using this quasi-horizontal coordinate system. In addition, the Eta uses the E-grid in horizontal and Lorenz grid in vertical. The time integration is done through a split-explicit scheme. It contains complete model physics processes. The shortwave radiation scheme is based on LACIS & HANSEN (1974), and the longwave radiation is based on FELS & SCHWARZKOPF (1975). The turbulence treatment is based on the Mellor-Yamada level 2.5 (MELLOR & YAMADA 1974). The convection parameterization uses the Betts-Miller scheme (BETTS & MILLER 1986) modified by JANJIC (1994). The cloud microphysics processes are parameterized using the Zhao scheme (ZHAO et al. 1997). The air-land-biosphere transfer processes are parameterized by the NOAH scheme (EK et al. 2003).

The Eta Model was integrated over the domain covering most of South America (between 12ºN and 50ºS, and 85ºW and 28ºW), with 20-km horizontal resolution and 38 vertical levels, and the model's top at 25 hPa. The global model simulations provide the initial and lateral boundary conditions, which are input into the Eta Model at a 6-hourly interval. The lower boundary condition over the ocean, the sea surface temperature, is taken from the global climate model sea surface. In contrast, over the continent, the present climatological surface moisture is adopted. The integration length of the simulations was 10 straight years, which is considered the minimum period to examine seasonal processes (JOUSSAUME et al. 1999). The initial distributions of ozone and albedo are taken from climatology, and the CO_2 adopts the same concentration as the global model. Some modifications were made to the Eta Model to make it suitable for paleoclimate simulations, mainly the inclusion of the Berger parameterization (BERGER 1978) which was also used by the Global Model.

The control simulations of the Eta Model precipitation for the present climate, 0k, were compared against the Modern Era-Retrospective Analysis for Research and Applications (MERRA) (RIENECKER et al. 2011) and Climate Research Unit (CRU) data (MITCHELL et al. 2004). Both observational datasets have a spatial resolution of 0.5°×0.5° (10-year average). The MERRA reanalysis data has precipitation values over the ocean.

10-year continuous simulation was carried out for the MH period by modifying the orbital parameters of the Eta (6k) Model. This simulation was compared with that of the present climate (0k). The difference between 6k – 0k shows the climate anomaly of the MH with respect to the present climate. Proxies are used to validate the Eta 6k Model simulation. The annual cycle of the shortwave radiation at the top of the atmosphere changes spatially and temporally due to the changes in the orbital parameters.

2.3 Paleoclimate Model

The orbital parameters (BERGER 1978) for the present and MH periods are shown in table 1.

TABLE 1 - Orbital parameters used in the simulations for global and regional climate models.

Orbital parameters	*Mid-Holocene 6k*	*Present 0k*
Obliquity	24.105	23.446
Excentricity	0.018682	0.016724
Precession	0.87	102.04

3 RESULTS AND DISCUSSION

The results are shown for seasonal averages of the trimesters December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON) to provide the annual climate variability.

The differences between the Eta 6k and the Eta 0k simulations provide the MH climate anomaly compared to the present climate. Analyses of the results refer to the regions: Amazon, Northeast, Central, Southeast, and South Brazil.

The statistical significance of the anomalies generated by the differences between MH and present was evaluated by the Student's t-test, which is generally adopted in climate sensitivity studies.

3.1 Orbital variation

Due to the insertion of modified orbital parameters in the model to reproduce the MH, it is necessary to verify the simulated variations in the amount and spatial distribution of the shortwave radiation at the top of the atmosphere. Figure 1 shows the global climate model amount of zonal mean (average of all longitudes around a latitude

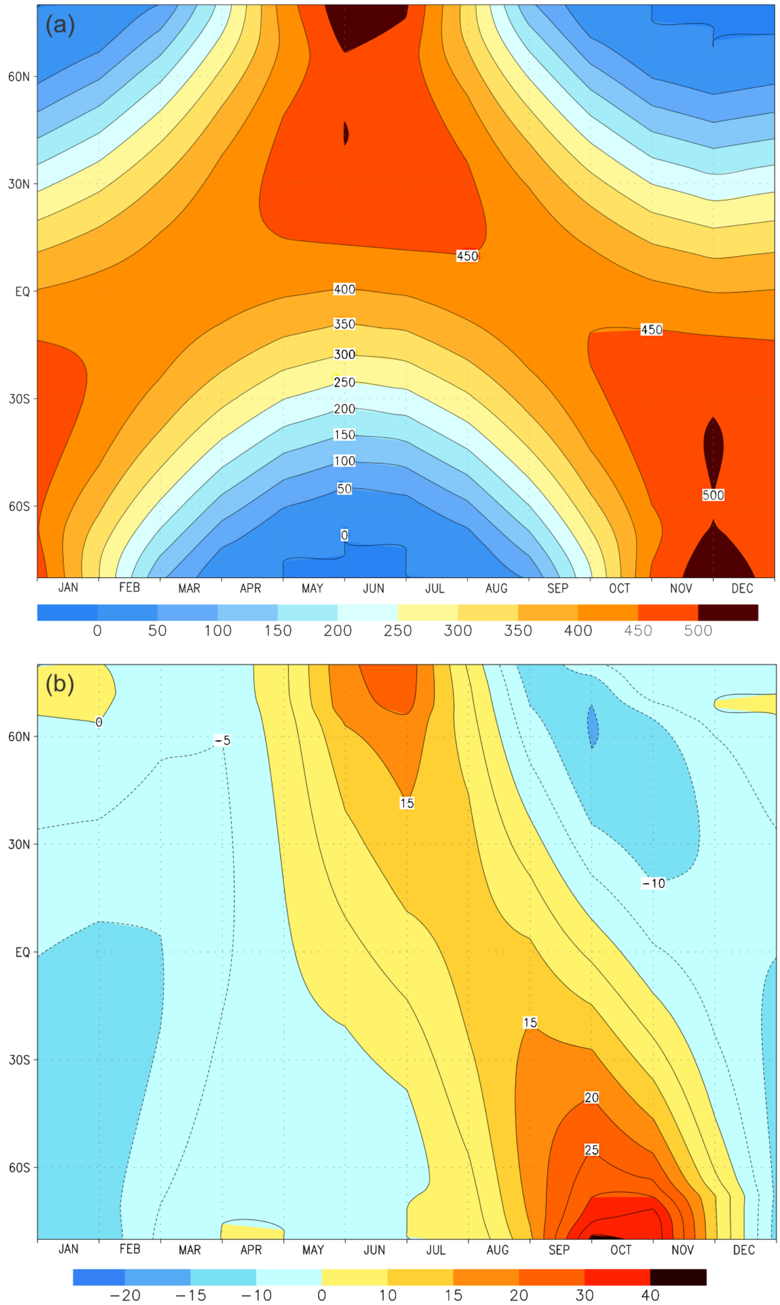

FIGURE 1 – Zonal mean shortwave radiation (Wm^{-2}) at the top of the atmosphere, using Berger parameterization for 6k (BERGER 1978) (a); Difference (Wm^{-2}) 6k - 0k (b).

circle) shortwave radiation (SWR) reaching the top of the atmosphere in the MH climate, Global 6k, along the year, and the difference in the SWR amount between the MH period and the present climate. Therefore, the change of the orbital parameters in global 6k concerning the Global 0k produced changes to the SWR. The symbols MH and 6k or present climate and 0k are used interchangeably throughout the text.

During MH, the Northern Hemisphere was closer to the Sun in boreal summer (JJA), while the Southern Hemisphere was closer to the Sun in the transition season of the austral spring (SON) in comparison with the present climate. As a result, more shortwave radiation reached the top of the planet's atmosphere between May and November in the Northern Hemisphere. The maximum insolation during the MH is simulated in the austral spring (SON) between 30ºS and 90ºS. This result agrees with SILVA DIAS et al. (2009).

Between June and August (JJA) in the Northern Hemisphere, during the MH, the average insolation increased by 20 Wm^{-2} to the north of 60^{o} N. In contrast, in the Southern Hemisphere, between September and December, the average insolation reached values above 20 Wm^{-2}, to the south of the latitude 45^{o}S, compared with the present period. For the months between December and May, DJF and MAM, the average insolation was smaller by about 10 Wm^{-2}, in both Hemispheres, in 6k compared to the present climate, 0k. Similar results for shortwave radiation reaching the top of the atmosphere were also found by BERGER (1978), JOUSSAUME & BRACONNOT (1997), VETTORETTI et al. (1998), MELO & MARENGO (2008), and VARMA et al. (2012).

3.2 Precipitation during MH

The Eta model simulated mean precipitation for the MH and reproduced its seasonal variations along the year (Figure 2). DJF is the season of more significant amounts of precipitation in the central part of the continent, which forms the South Atlantic Convergence Zone precipitation band. JJA is the season with the least amount of precipitation. This seasonal cycle of the precipitation pattern during 6k is similar to 0k. The precipitation differences between Eta 6k – Eta 0k show that, in general, in the central part of Brazil, there was less precipitation than the present climate, except for the SON season, when the simulated precipitation amount was larger.

In Northeast Brazil, 6k simulation is more humid, up to about 3 mm/day in some areas in most of the seasons, except in the MAM, when negative differences are shown in parts of the north and west of Northeast Brazil. The difference between 6k and 0k in Northeast Brazil has high statistical significance according to the Student's t-test with a 5% error.

In the central and southern parts of the Amazon region, the 6k climate was generally drier. However, some spotty areas with more significant precipitation amounts are found north and northeast of the Amazon during the DJF, MAM, and SON seasons. The ITCZ position over the Atlantic and the Pacific oceans may have affected the precipitation in the Amazon region.

In South Brazil, the Eta simulation of MH produced less precipitation than in 0k, mainly during SON and in the state of Rio Grande do Sul. The northern states of Paraná and Santa Catarina were wetter, especially in MAM months. These differences for South Brazil have high statistical significance based on the Student's t-test.

In Southeast Brazil, the simulated amounts of precipitation were generally smaller, indicating a drier climate compared to the present, particularly during DJF, the rainy season of this region. Therefore, the reduction in precipitation of about 3 mm/day at the present South Atlantic Convergence Zone is significant at test levels of 5%. This drier climate indicates a less active SACZ, a unique feature of the rainy season. On the other hand, in Central Brazil, the precipitation amounts were generally more significant; therefore, the MH simulation indicated a wetter climate, particularly during DJF and SON.

3.3 Outgoing Longwave Radiation during MH

These characteristics of precipitation during the MH can be confirmed by the outgoing longwave radiation (OLR) (Figure 3), whose minimum fluxes are found over the regions of maximum precipitation, such as those related to the ITCZ, SACZ, and the Amazon region. The minimum OLR is a response to deep convective clouds' activity.

In DJF, the area of minimum OLR corresponds to the area of a more significant difference between 6k OLR and 0k OLR; therefore, larger values of 6k OLR indicate lower convective cloud tops and less active SACZ. On the other hand, part of the ITCZ, which was positioned over the Equatorial Atlantic and Northeast Brazil, had

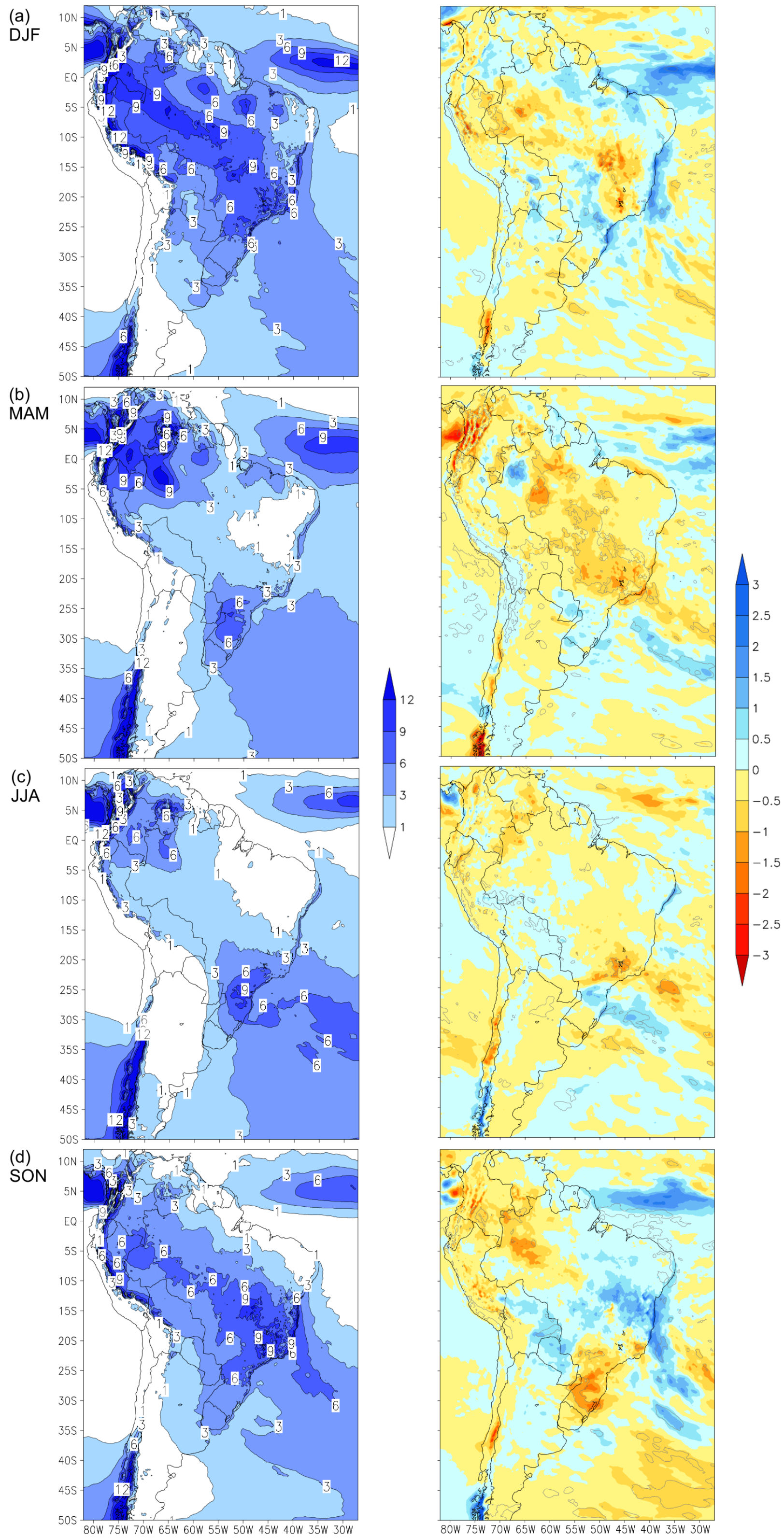

FIGURE 2 – Seasonal mean precipitation (mm/day) during MH (left column) and the difference (right column) of seasonal mean precipitation between the Mid-Holocene and the present (6k-0k). a) DJF; b) MAM; c) JJA and d) SON. Contoured areas in grey indicate high statistical significance by the Student t-test.

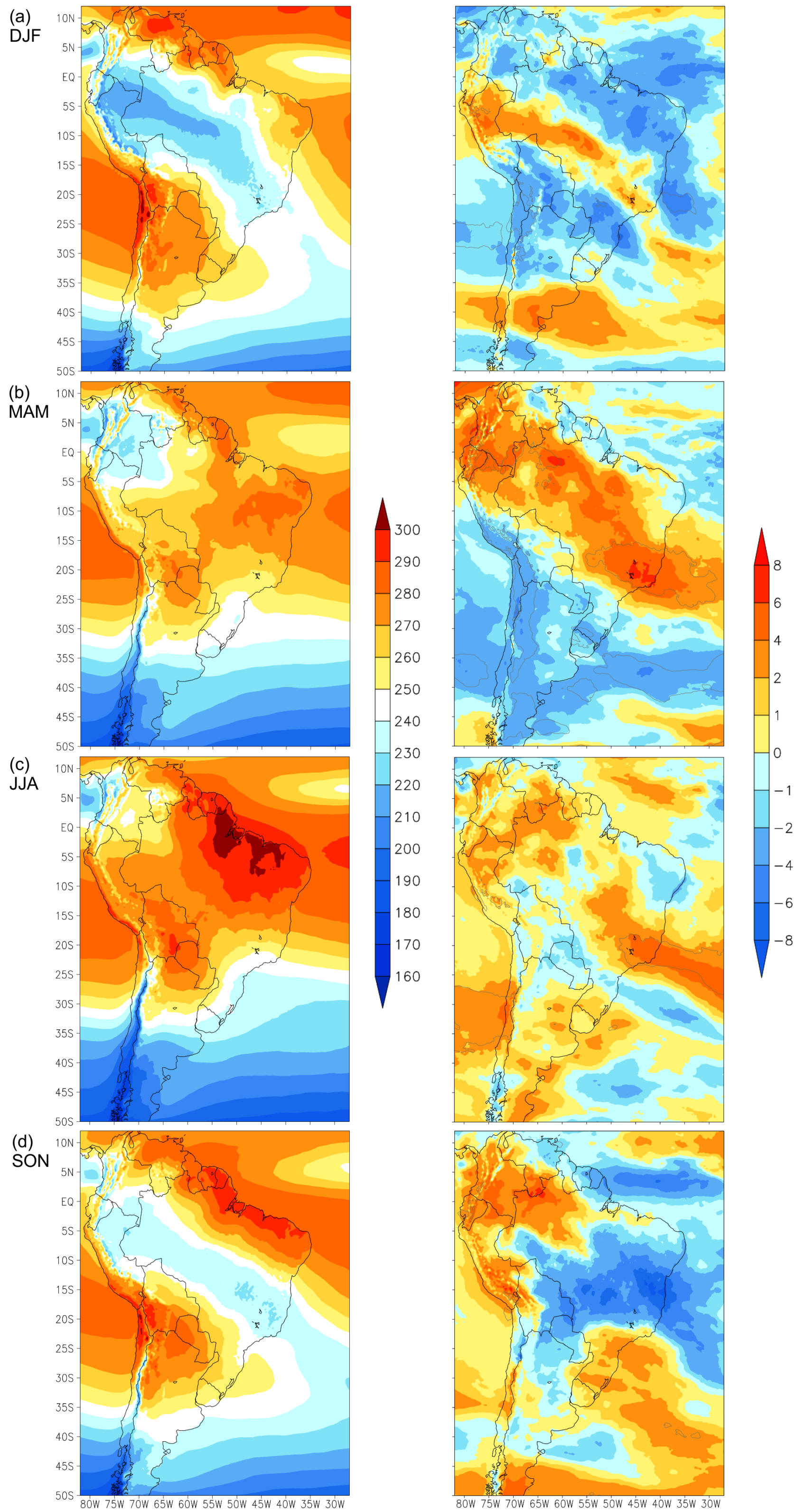

FIGURE 3 – Seasonal mean Outgoing Longwave Radiation (OLR) (Wm^{-2}) for the MH (left column) and the difference (right column) of seasonal mean OLR between the Mid-Holocene and the present (6k-0k). a) DJF; b) MAM; c) JJA and d) SON. Contoured areas in grey indicate high statistical significance by Student's t-test.

deeper convective clouds and, therefore, more precipitation, as seen in figure 2.a.

During MAM and JJA in 6k, the Southeast of Brazil was more cloud-free, or there were not as deep clouds as in the present climate. During the SON, the large negative difference of 6k – 0k OLR over Northeast and Central Brazil agrees with more precipitation in this season.

3.4 2-meter temperature during MH

The mean 2-meter temperature simulated for the MH by the Eta Model (Figure 4) shows the seasonal variation similar to the present climate, when cooler temperature occurs in Central, Southeast, and South Brazil during winter, in JJA, and warmer temperature occurs during summer, in DJF. In the Amazon region, the warmest temperatures occur during JJA and SON.

The climate in MH was generally cooler than the present climate. This coolness is widespread throughout South America during the DJF, reaching up to 0.8ºC in some regions, and has high statistical significance (above 95%) according to the Student's t-test.

In Northeast Brazil, negative temperature differences of up to 0.8ºC are found in parts of the region in all seasons, with a high significance based on Student's t-test, except for some regions on the northern and northeastern coast, where temperatures show almost no difference in comparison with the present climate. A similar cooler climate was found in Central Brazil, where temperature differences of up to 0.8ºC are simulated with high statistical significance. In the South, the simulated temperatures during 6k are also generally cooler, except in SON, when temperatures are warmer with differences up to 0.4ºC. The Southeast MH climate was cooler in SON and DJF and warmer in MAM and JJA compared to the present climate. These differences range from about -0.2 up to about 0.4ºC. On the other hand, the simulations generally reproduce the warmer Amazon regions for the MH in most seasons, except in DJF, when temperatures are cooler, mainly in the central part, compared with the present days.

In general, the simulation of MH by the Eta model suggests cooler air in most of South America. The western part of the Amazon region is an exception, where warmer temperatures occur in most seasons.

3.5 Lower-level circulation during MH

The seasonal mean wind vector at 850 hPa simulated for the MH (Figure 5) generally shows the standard circulation features over South America: the anticyclonic circulation over the adjacent Atlantic and Pacific Oceans, the strong easterlies over the equatorial region, and the strong westerlies over the mid-latitudes. The equatorial easterly winds blow from the Atlantic Ocean, extend into the continent and reach the Andes Cordillera, where the winds turn southward and southeastward. The simulated subtropical high over the South Atlantic during MH shows significant differences, which consequently alter the intrusion of cold air across the continent.

During the DJF, the northeasterly trade winds are more intense in MH, which causes the displacement of the ITCZ toward a more southern position than in 0k. In the MH, the average ITCZ position at about 2º S provided more precipitation in Northeast Brazil than in the present 0k. Wind convergence in the southern part of the Amazon region was weaker during 6k, which may have caused less precipitation production (see Figure 1a).

The differences between the 850-hPa winds between the 6k and 0k 850-hPa winds show that in the southern Amazon, a westerly wind component difference is a sign of the weaker moisture transport from the Amazon region toward Central, South, and Southeast Brazil. This reduced moisture transport affects the formation and position of the SACZ and reduces precipitation in these regions. These results were also found by DEWES (2007) and MELO & MARENGO (2007).

During MAM of the MH, the trade winds show weakening in the ITCZ. In addition, over Central Brazil and the southern part of the Amazon, easterly winds blow stronger and bring cooler air from the adjacent Atlantic Ocean into the continent. In South Brazil, the winds acquire more westerlies, which may bring more moisture from the Amazon and strengthen the anticyclonic circulation over the continent compared to 0k.

During JJA, the 850-hPa winds show the southern Atlantic anticyclone with stronger easterly winds in 6k than in 0k, and these easterlies penetrate the continent more strongly over Southeast Brazil. On the other hand, the easterlies around the equatorial region are weaker during MH, which may have caused a reduction in moisture transport into the Amazon region, and, therefore, less production of precipitation in this region during 6k.

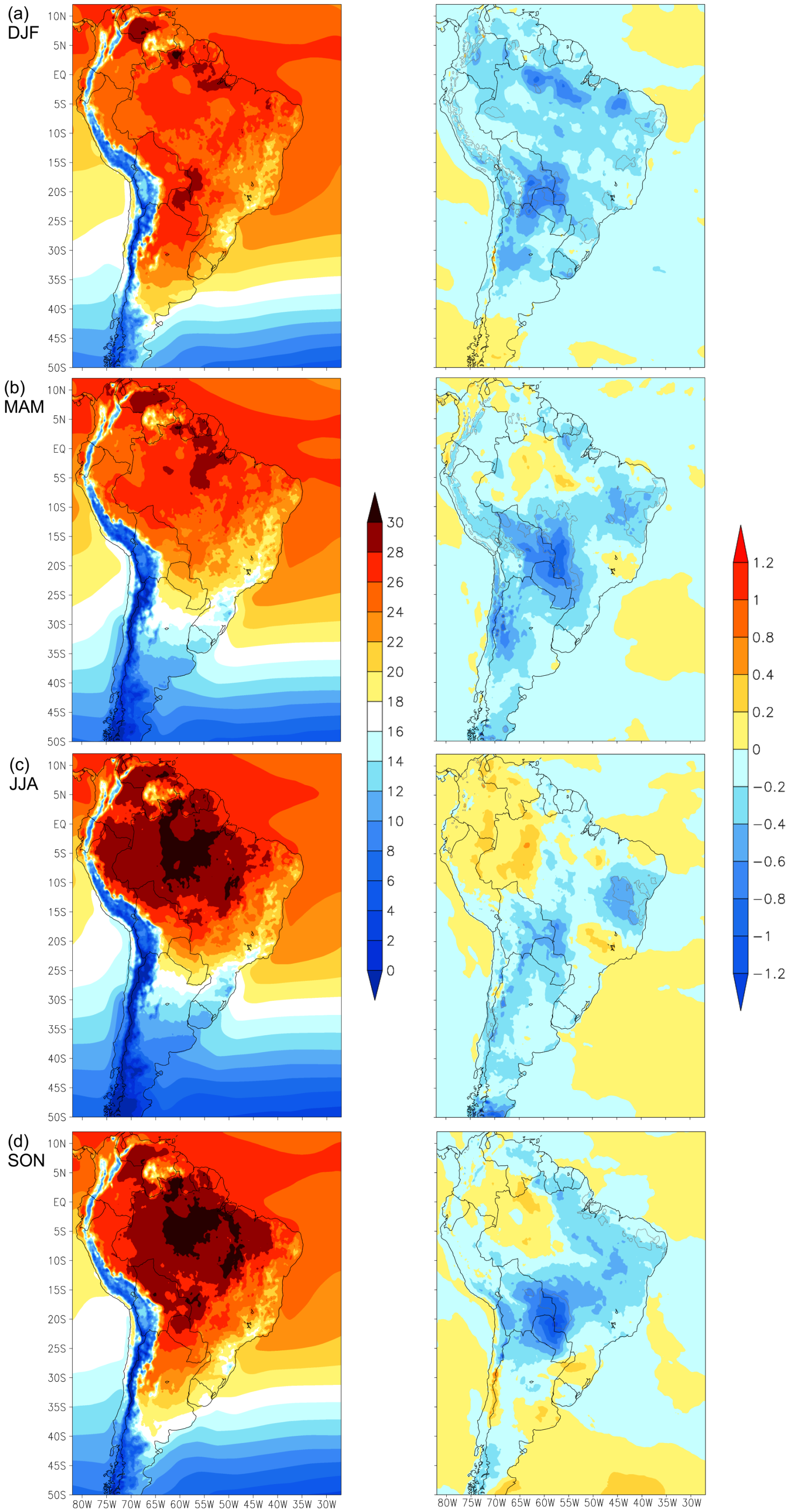

FIGURE 4 – Seasonal mean 2-meter temperature (ºC) for MH (left column) and the difference (right column) of seasonal mean 2-meter temperature between the MH and the present (6k-0k). a) DJF; b) MAM; c) JJA and d) SON. Contoured areas indicate high statistical significance by Student's t-test.

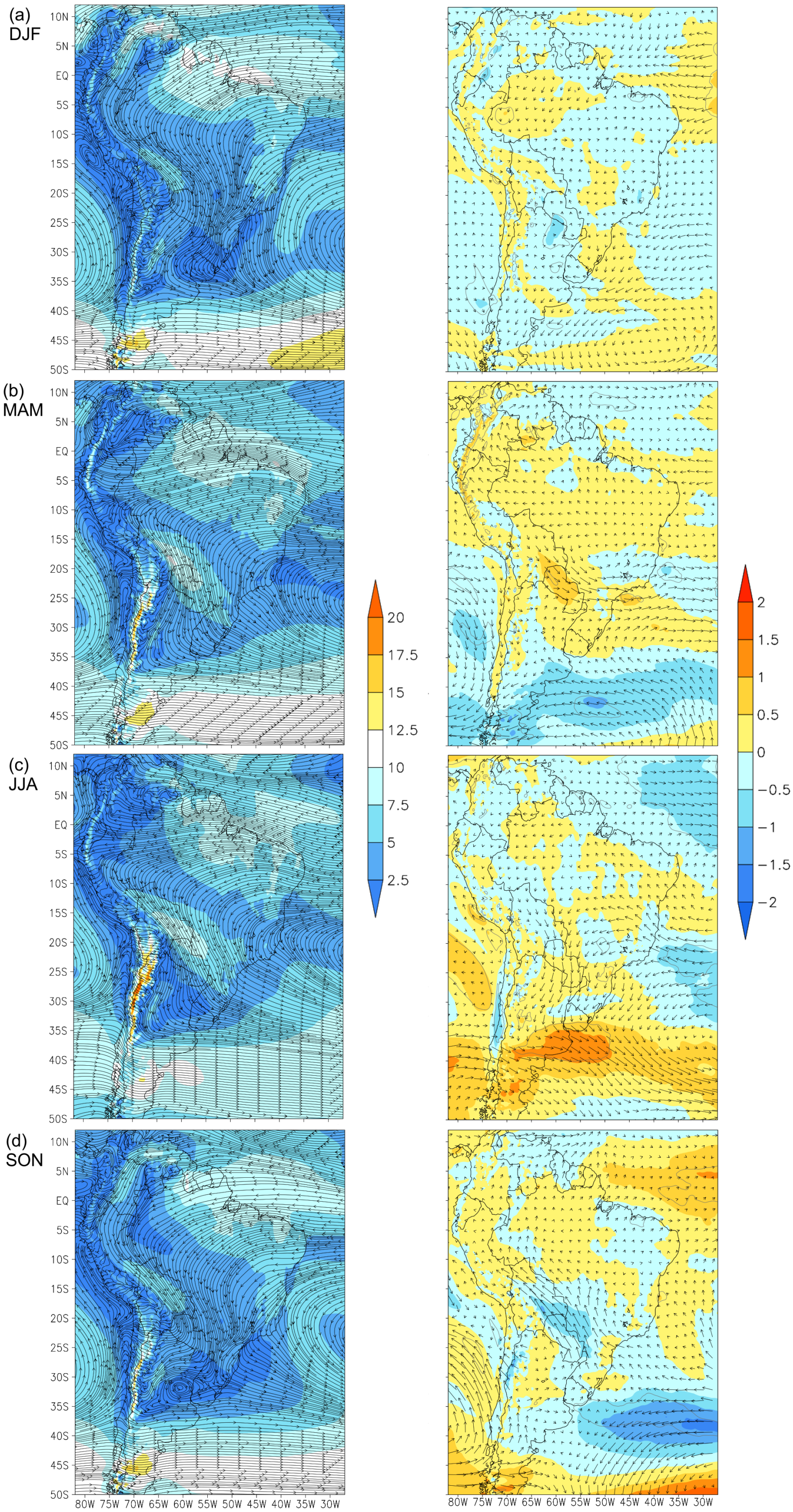

FIGURE 5 – Seasonal mean 850-hPa winds (m/s) for MH (left column) and the difference (right column) of seasonal mean 850-hPa winds between the Mid-Holocene and the present (6k-0k). a) DJF; b) MAM; c) JJA and d) SON. Contoured areas indicate high statistical significance by Student's t-test.

During SON, in the 6k, the Low-Level Jet (LLJ) (MARENGO et al. 2002) to the east of the Andes, around Bolivia, is weaker than in 0k. The LLJ is a significant circulation feature of South America as it transports moisture from the Amazon basin toward the La Plata Basin and plays a crucial role in the frontogenesis over northern Argentina. This weaker moisture transport caused smaller amounts of precipitation in South Brazil during 6k, SON.

In summary, the LLJ to the east of the Andes, which transports moisture from the Amazon region to central and southeastern Brazil, is less intense in the MH during SON and DJF and stronger during MAM and JJA. Results were also found by MELO & MARENGO (2008) using the global atmospheric model.

3.6. Paleoclimate signals

The Eta Model simulations of MH using the Berger parameterization were validated by comparing the simulations against paleoclimate data (proxies) calibrated by GORENSTEIN et al. (2022) hereafter referred to as GO22. The authors compiled 173 (total) studies, consisting of different paleoarchives: 19 speleothems, 145 sediment cores (13 marine, 63 lacustrine, and 69 terrestrial), and 8 soil samples from South America, and used methodology similar to PRADO et al. (2013a, b) to describe the major proxy types. A regional interpretation of the results was obtained following the IPCC AR5 Reference Regions (IPCC 2014) by dividing Eastern SA into 3 regions. Southern SA, Amazonia, and NE Brazil. The list of the locations where proxies are available can be found in GO22 Supplementary Material.

The spatial distribution of the simulated precipitation regime during MH is evaluated by comparing the simulated mean precipitation difference 6k - 0k and the proxy data (Figure 6). Seasonal variability can no longer be distinguished from the proxy data.

The GO22 data indicates that the MH was overall drier than present in the Amazon region. The simulations of the Eta Model for 6k agree with the proxies. In this region, the GO22 data contains 37 precipitation proxy records, among which: 30 data studies, mainly with biological proxy analysis, point to a drier MH; 4 data suggest wetter than the present; and 3 similar to the present. The drier climate indicates an overall weakening of the South American Summer Monsoon (SASM) during the MH, which validates the Eta simulations. The lower lake levels (GO22; TURCQ et al. 2002) or complete dry up (SIMÕES FILHO et al. 1997) records found in the Amazon confirm the overall drier climate during MH in this region.

In Northeast Brazil, the palynological records of Saquinho revealed more developed forests during the MH (DE OLIVEIRA et al. 1999), which suggests a more humid climate. MAYLE et al. (2000) and HAUG et al. (2001) also found a more humid climate in their studies; in agreement, this regime is also simulated by the Eta RCM. There is also some difficulty in evaluating the results of changes in precipitation because this region is located in the transition between the wettest and driest zones. On the other hand, the GO22 dataset contains 43 precipitation proxy records for the NE Brazil region, with 6 data pointing to a wetter MH, 11 similar, and 26 a drier MH compared to the present. These results indicate more southern incursions of the ITCZ across the continent during MH, in agreement with PRADO et al. (2013a, b). In the western part of Northeast Brazil, in the area so-called Interior Sites by GO22, although the Eta simulations show wet conditions this disagree with the GO22 dataset that shows drier conditions.

In Central Brazil, the records in the Feia Lake (site #104 in GO22) (TURCQ et al. 2002), as well as the palynological records of Águas Emendadas (site #31) (BARBERI et al. 2000) and Crominia (site #39) (SALGADO-LABOURIAU et al. 1997), they all indicate drier climate conditions during the MH; therefore, the Eta 6k simulation is in agreement with these site proxies and GO22 dataset. However, on the western part, bordering Bolivia, the GO22 dataset shows drier climate, whereas the simulations are transitioning to a wetter climate.

In Southeast Brazil, in general, GO22 proxies show drier climate in MH than in present. The Eta Model simulated less precipitation in this region during the MH than the present in agreement with these proxies. On the other hand, some proxies suggest that the MH period was more humid around the Paraíba do Sul river basin and the southern part of Rio de Janeiro state, the MH period was more humid (COELHO et al. 2002, GARCIA et al. 2004), as indicated by GO22 data. Although the Eta Model simulation shows an overall drier climate in this part of the region, it indicates a wetter climate with positive precipitation differences in the rainy months, DJF, which shows agreement with the precipitation regime in this area. The Dom

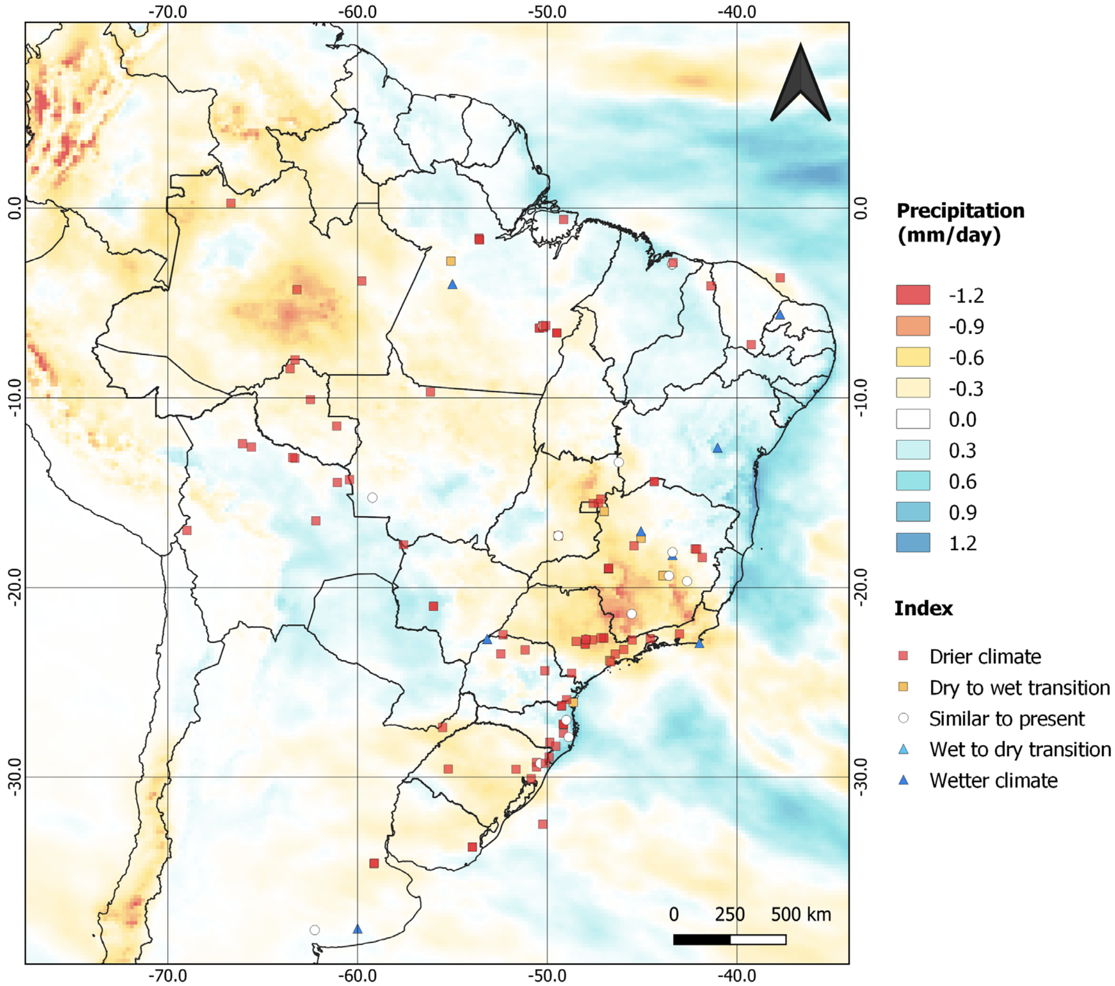

FIGURE 6 – Difference between simulated 6k and 0k precipitation (mm/day). The symbols indicate proxies for precipitation regimes : (□) for dry, (△) for wet, and (○) for similar climates compared to the present climate. These proxy points are derived from GORENSTEIN et al. (2022).

Helvécio (proxy #103) and Preta de Baixo lakes (proxy #102) had lower water levels during the MH (TURCQ et al. 2002); the same was found in Santa Lagoon (proxy #32), according to PARIZZI et al. (1998). Therefore, the lower level of these lakes indicated the drier climate that was simulated by the Eta Model in this region. Several other studies agree in a drier climate in Southeast Brazil during MH (LEDRU 1993, BEHLING 1997, SALGADO-LABOURIAU et al. 1997, PESSENDA et al. 2005)

In South Brazil, overall, the GO22 proxy show drier climate. In this region, GO22 dataset contains 60 precipitation proxy records, among which 3 point to a wetter MH, 8 similar, and 49 a drier MH compared to the present. However, in the Boa Vista mounts (proxy #20), the records show an expansion of the Atlantic rainforest (BEHLING 1995). Near the eastern coast, several proxy point to drier climate. This is a region of complex topography with high mounts and next to coastal areas. In the Rio Grande do Sul, the southernmost state in Brazil, the Eta simulation produces reduced precipitation for 6k compared with 0k. However, there is some intra-annual variability, as the precipitation difference simulated for MAM shows slightly increased precipitation for 6k (Figure 2b). The water deficit scenario is associated with weaker SASM activity due to weaker ENSO variability. Therefore, the Eta simulations of the MH for South Brazil agree with the proxies but along the coast, the GO22 had a drier climate, which was not simulated.

The Eta simulated mean 2-m temperature for MH showed a cooler climate than the present for most of the country (Figure 7), except over the Amazon, where a slightly warmer climate was simulated for MH.

4 CONCLUSIONS

The Berger parameterization (BERGER 1978), which calculates the orbital parameters for eccentricity, obliquity, and precession, was included in the regional Eta Model. This RCM used the same parameters as the driver model, the INPE's Global Atmospheric Model. The Eta RCM simulated the Mid-Holocene and present climate, taking 10-year timeslices of both periods.

The simulation of the present climate by the Eta Model reproduced the significant features of the South American climate, such as the seasonal latitudinal displacement of the ITCZ, the cloud band of the SACZ, the Subtropical High of the South Atlantic, the South American Low-Level Jet. These features showed that the modified Eta Model could reproduce the present climate of South America from the downscaling of the global climate model.

The Eta Regional Paleoclimate Model developed in this work was further assessed by the simulation of paleoclimate characteristics of the MH period in Brazil. Changes in the Earth's orbital parameters (eccentricity, obliquity, and precession) for the MH period caused changes to the seasonal cycle of insolation in both hemispheres. The global climate model attenuated the seasonal cycle in the Southern Hemisphere, and this signal was transferred to the RCM.

The comparison of the Eta Model MH simulations against paleoclimate calibrated proxies from GO22 showed that, in general, the model reproduced the significant differences of the Mid-

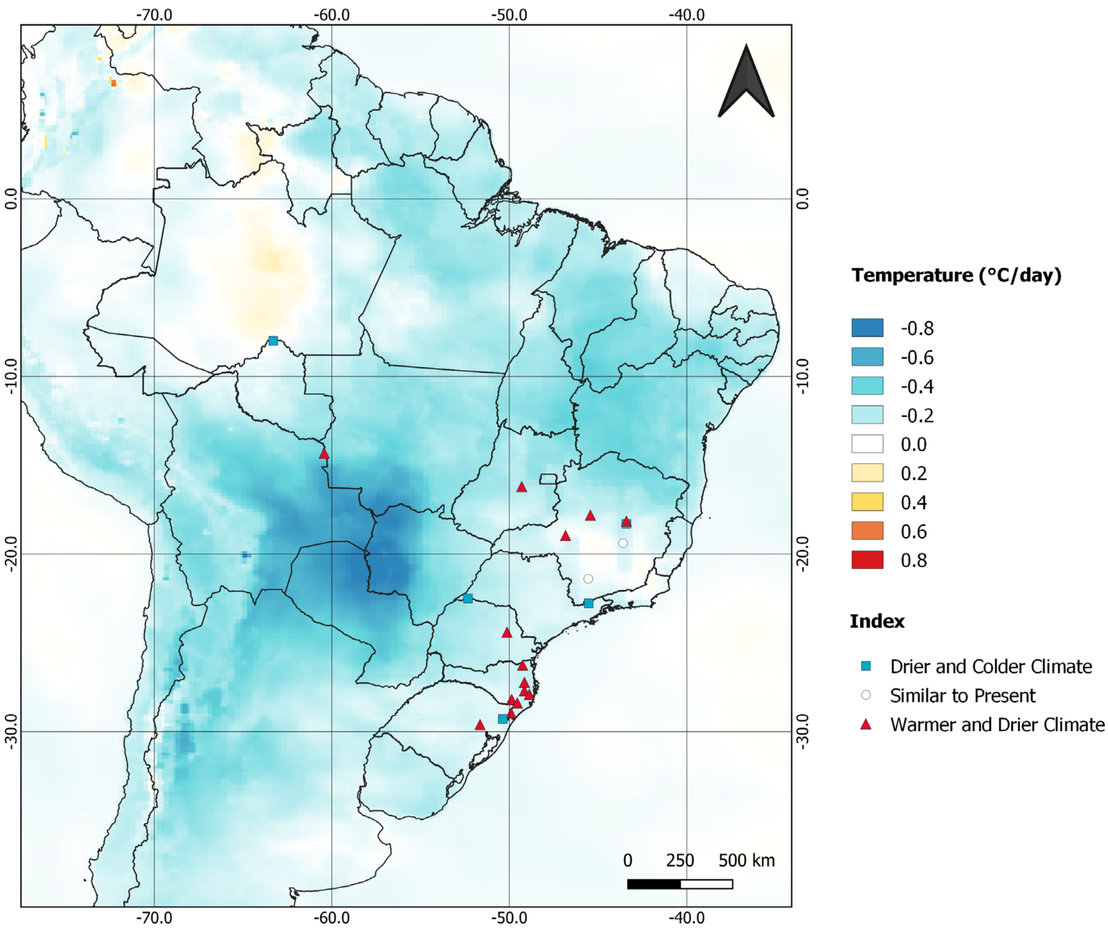

FIGURE 7 – Difference between simulated 6k and 0k 2-m temperature (°C). The symbols indicate proxies for temperature regimes: (□) for cooler, (△) for warmer and (○) for similar climates compared to the present climate. These proxy points are derived from GORENSTEIN et al. (2022).

Holocene period, such as the drier climate in the Amazon region, wetter in parts of the Northeast, drier in most of Southeast, and drier in parts of the South. The country had an overall cooler climate than the present. The modeling studies carried out by VALDES (2000), MELO & MARENGO (2008), and SILVA DIAS et al. (2009) also compared reasonably well with the proxies; however, those results were obtained from coarse global climate models. On the other hand, this work showed that a regional paleoclimate model, based on the eta vertical coordinate, provided downscaling to 20-km resolution and detailed the paleoclimate conditions in the region. The evaluation showed that the model in its paleoclimate version is suitable for carrying out climate change simulations for the Mid-Holocene climate. Other past climate periods will be tested in the future.

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